IS AMINO-ACID HOMOCHIRALITY DUE TO ASYMMETRIC PHOTOLYSIS IN SPACE?

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Abstract. It is well known that the amino acids occurring in proteins (natural amino acids) are, with rare exceptions, exclusively of the L-configuration. Among the many scenarios put forward to explain the origin of this chiral homogeneity (i.e., *homochirality*), one involves the asymmetric photolysis of amino acids present in space, triggered by circularly polarized UV radiation. The recent observation of circularly polarized light (CPL) in the Orion OMC-1 star-forming region has been presented as providing a strong, or even definitive, validation of this scenario. The present paper reviews the situation and shows that it is far more complicated than usually apprehended in the astronomical literature. It is stressed for example that one important condition for the asymmetric photolysis by CPL to be at the origin of the terrestrial homochirality of natural amino acids is generally overlooked, namely, the asymmetric photolysis should favour the L-enantiomer for *all* the primordial amino acids involved in the genesis of life (i.e., biogenic amino acids). Although this condition is probably satisfied for aliphatic amino acids, some non-aliphatic amino acids like tryptophan and proline may violate the condition and thus invalidate the asymmetric photolysis scenario, assuming they were among the primordial amino acids. Alternatively, if CPL photolysis in space is indeed the source of homochirality of amino acids, then tryptophan and proline may be crossed out from the list of biogenic amino acids. Laboratory experiments suggested in this paper could shed further light on the composition of the set of amino acids that were required for development of the homochirality of first life.

1. The Origin of Amino Acid Homochirality: A Long-Standing Question

Proteins play a crucial role in life, taking part in all vital processes. The building blocks of proteins are the amino acids. They consist of a central carbon atom (called α-carbon) bound to four groups: an amino or basic group (NH_2), an

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acid group (COOH), a hydrogen atom, and a variable group R, called side chain, that makes the specificity of each amino acid. Only 20 different amino acids are used as building blocks in today's proteins; they constitute the set of so-called *natural* amino acids. The primordial amino acids involved in the genesis of life constitute the set of *biogenic* amino acids. In the following, we will assume that some (if not all) of these primordial amino acids are now part of the set of natural amino acids.

Because the four chemical groups bound to the α-carbon of amino acids are not in a plane but rather adopt a tetrahedral shape (Fig. 1), all amino acids are chiral (except glycine whose R group is a hydrogen atom), i.e., they possess two non-superposable three-dimensional mirror image structures or enantiomers. The refractive indices of (a solution of) chiral molecules for clockwise and counterclockwise circularly polarized light are different, leading to a net rotation of the plane of linearly polarized light. By convention, molecules that make the polarization plane of sodium D light (at $\lambda = 589.3$ nm) turn to the right or to the left are called (+) or (−), respectively (note that, for several amino acids, the +/− assignment is different for acid, neutral or basic solutions; see Sect. 3). The +/− convention thus classifies enantiomers on the ground of their *optical rotatory power*. Several other classification schemes of enantiomers exist, based on their *geometrical conformation*. One of these compares the amino acid structure to that of a reference chiral molecule, namely glyceraldehyde. By convention, (+)-glyceraldehyde was assigned configuration D (from the Latin *dexter*, right), and (−)-glyceraldehyde was assigned configuration L (from the Latin *laevus*, left). Using some correspondence rule (see e.g., Morrison and Boyd, 1987), the considered amino acid structure can be superposed on either D- or L-glyceraldehyde, and it is classified as D or L accordingly. Since the D/L classification refers to the geometrical conformation whereas +/− refers to the optical rotatory power, there is not a one-to-one correspondence between the two assignments. Actually, only a small majority of the 19 chiral natural L-amino acids rotate the plane of polarized sodium light to the left, i.e., belong to the L-(−) type (in a neutral solution) (see e.g., Morrison and Boyd, 1987).

It is known since long ago that the natural amino acids are, with rare exceptions, exclusively of the L-configuration (Davies, 1977). The origin of this chiral homogeneity (i.e., *homochirality*) has been a puzzle since its discovery, and remains the subject of a warm debate (Cline, 1996; Podlech, 1999, and references therein).

Several mechanisms have been proposed, as reviewed e.g. by Bonner (1991) (see also the various contributions in Cline, 1996), which may be grouped into biotic and abiotic theories. The former ones assume that life originated on Earth through chemical evolution in a primordial racemic (i.e., containing equal amounts of the L- and D-enantiomers) milieu, and that chiral homogeneity inevitably resulted from the evolution of living matter. Gol'danskii and Kuz'min (1988) convincingly argued, however, that a biotic scenario for the origin of chiral purity is not viable in principle, since without preexisting chiral purity the self-replication characteristic of living matter could not occur. This argument thus strongly favours abiotic theories which may be grouped into the following

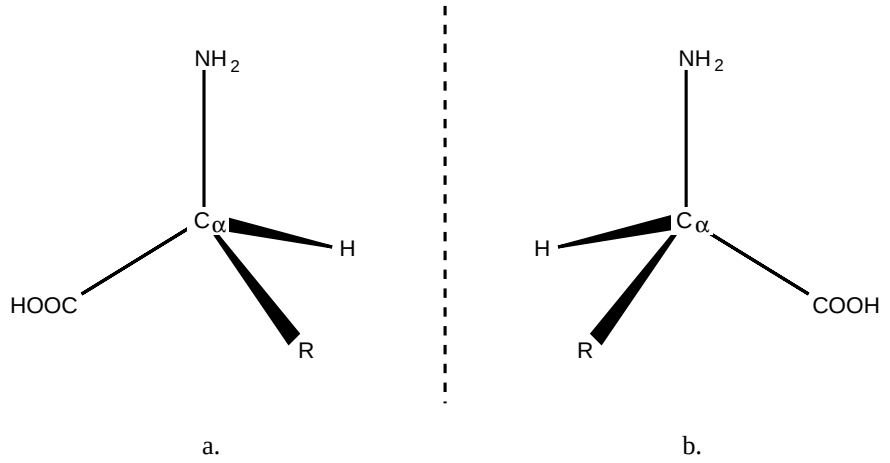

Figure 1: a. L-amino acid; b. D-amino acid

classes (Bonner, 1991): chance mechanisms (spontaneous symmetry breaking by stereospecific autocatalysis, spontaneous resolution on crystallization, asymmetric synthesis on chiral crystals, asymmetric adsorption) and determinate mechanisms, the latter being subdivided into regional/temporal processes (symmetry breaking induced by electric, magnetic or gravitational fields, by circularly polarized light via asymmetric photoequilibration, photochemical asymmetric synthesis or asymmetric photolysis) and universal processes (violation of parity in the weak interaction).

Only the hypothesis of symmetry breaking by the action of circularly polarized light (CPL) will be discussed in some details in this paper. The role of CPL present in natural skylight as a chiral engine was already suggested in the nineteenth century by Le Bel (1874) and van t'Hoff (1894). More recently, a similar scenario invoking the asymmetric photolysis of amino acids taking place not on Earth but rather in space (probably in the organic mantles at the surface of interstellar grains) has been put forward by several authors (Norden, 1977; Rubenstein et al., 1983; Bonner and Rubenstein, 1987; Bonner, 1991; Bonner, 1992; Greenberg et al., 1994; Greenberg, 1997). After some debate regarding the possible role of CPL from pulsars (Rubenstein et al., 1983; Roberts, 1984; Bonner and Rubenstein, 1987; Greenberg et al., 1994; Engel and Macko, 1997; Mason, 1997; Bonner et al., 1999), this idea regained interest recently with the observation of CPL in the Orion OMC-1 star-forming region (Bailey et al., 1998).

2. Asymmetric Photolysis: A Cosmic Enantioselective Engine?

Asymmetric photolysis, first demonstrated successfully by Kuhn and cowork-

ers (1929, 1930a, 1930b) involves the preferential destruction of one enantiomer during the photodegradation of a racemic mixture by CPL. CPL-mediated reactions depend on the circular dichroism (CD) of the reactant (Crabbé, 1965; Buchardt, 1974; Rau, 1983), i.e., on the difference in its molar absorption coefficients $\epsilon_{(-)}$ and $\epsilon_{(+)}$ for (−)-CPL (left CPL) and (+)-CPL (right CPL), respectively [$\Delta\epsilon = \epsilon_{(-)} - \epsilon_{(+)} \neq 0$]. Note that here the difference in *molar absorption coefficients* is involved, not the difference in *refractive indices* (they are nevertheless related via the Kramers-Kronig integral relation (see e.g., Cantor and Schimmel, 1980). Since the photolysis rate depends upon the amount of light absorbed by the reactant, CD thus leads to different reaction rates for the two enantiomers, inducing an enantiomeric asymmetry as the reaction proceeds. Asymmetric photolysis, as considered here, results in the preferential destruction of the enantiomer having the higher absorption coefficient. The efficiency with which photolysis yields an enantiomeric excess is directly related to the so-called anisotropy factor $g = \Delta\epsilon/\epsilon$, where $\epsilon = (\epsilon_{(-)} + \epsilon_{(+)})/2$ (Kuhn, 1930; Balavoine et al., 1974). In the spectral region where $\Delta\epsilon \neq 0$, the molecule is said to have a CD band, which corresponds to an absorption band of the pertinent chromophore in the substrate.

The electronic absorption bands of amino acids occur in the UV (shortwards of 300 nm) (Donovan, 1969), and most are optically active. Successful asymmetric photolyses of amino acids were performed by Flores et al. (1977) (2.5% enantiomeric excess in leucine after 75% photolysis of a racemic mixture), Norden (1977) (0.22% excess in glutamic acid after 52% photolysis, 0.06% excess in alanine after 20% photolysis), and Greenberg et al. (1994) (3% excess after irradiating racemic tryptophan at 10 K for 50 hours with monochromatic light at 252.4 nm with about 10^{12} photons cm^{-2} s^{-1}).

In his review on the *Origin and Amplification of Biomolecular Chirality*, Bonner (1991) concludes that an extraterrestrial origin of the biological homochirality on Earth seems the most likely. This author suggests that an enantiomeric excess in amino acids originated in space as a result of asymmetric photolysis triggered by CPL (Norden, 1977; Rubenstein et al., 1983; Bonner and Rubenstein, 1987; Greenberg et al., 1994; Greenberg, 1996), and was somehow transported to the prebiotic Earth. This scenario received further support recently from the detection of IR CPL in the Orion OMC-1 star- forming region (Bailey et al., 1998).

In order for such a scenario to work, several conditions must be met: (i) amino acids must be able to form in an extraterrestrial environment; (ii) UV CPL must be present in space to irradiate these extraterrestrial amino acids; (iii) all the biogenic L-amino acids must have a CD spectrum such that the photolysis by CPL of a given sign produces an excess of the L-enantiomer for all of them; (iv) amino acids must be transported from space onto the primitive Earth e.g. via cometary and asteroidal impacts or via accretion of interstellar grains when the Earth traverses molecular clouds. They must survive the heat generated during the passage through the atmosphere and the impact with the surface; (v) amplification mechanisms are required to bring the small excess induced by asymmetric photolysis to complete homochirality.

Most of these conditions remain speculative, though with very different levels of uncertainty. The proof of (i) would require the direct detection of amino acids in space, which has not yet been achieved with certainty, despite several attempts (Miao et al., 1994; Travis, 1994, Combes et al., 1996). Indirect arguments in favour of an exogenous synthesis of amino acids are however provided by the discovery of apparently extraterrestrial amino acids in the Cretaceous/Tertiary boundary sediments (Zhao and Bada, 1989; for critical assessments, see Cronin, 1989, Chyba et al., 1990, Chyba and Sagan, 1992), and in the Murchison meteorite (Kvenvolden et al., 1970; Engel and Nagy, 1982; Engel et al., 1990, Engel and Macko, 1997; Cronin and Pizzarello, 1997, and references therein; for a critical assessment, see Cronin and Chang, 1993, and Pizzarello and Cronin, 1998). Moreover, laboratory experiments that simulate the formation of the organic mantles on interstellar grains by the action of UV light have been able to produce amino acids (Mendoza-Gómez, 1992; Greenberg, 1997).

The detection of CPL in the Orion OMC-1 star-forming region by Bailey et al. in 1998 (condition ii) gave a new impetus to asymmetric photolysis in space as a cosmic enantioselective engine. The large (17%) circular polarization reported in Orion OMC-1 was observed in the IR domain, though amino acids CD bands are located shortward of 300 nm. Nevertheless, model calculations seem to indicate that, if CPL is produced by scattering on nonspherical grains aligned in a magnetic field, similar circular polarization levels should be attained in the UV and IR domains (Bailey et al, 1998). Somewhat lower circular polarization levels were reported previously in the Chamaleon low-mass star-forming region (Gledhill et al., 1996) and around the pre-main sequence object GSS30 (Chrysostomou et al., 1997).

Transport of amino acids from space to the prebiotic Earth (condition iv) and amplification of a small exogeneous enantiomeric excess (condition v) seem possible as well, as shown by detailed studies (Chyba et al., 1990; Bonner, 1991; Chyba and Sagan, 1992; Greenberg et al., 1994).

Thus, only condition (iii), i.e., the possibility of forming the same enantiomer for *all the biogenic amino acids* by asymmetric photolysis, has not yet been the subject of a critical assessment in order to validate the above scenario (although a weaker form of this condition was already expressed by Mason, 1997). In fact, the assessment of condition (iii) requires the knowledge of both the composition of the set of biogenic amino acids, and their CD spectrum in the conditions prevailing in space (e.g., solid or gas phase, temperature). Both of these are unknown, unfortunately. Nevertheless, the consideration of CD spectra of natural amino acids in liquid solution may already provide some useful information, as shown in Sect. 3.

3. CD Properties of Amino Acids

The possibility that the terrestrial homochirality of amino acids originated from asymmetric photolysis by CPL in space requires that the L-enantiomer be favoured for all the biogenic amino acids. In other words, this requirement

implies that the substrate was irradiated by CPL in a spectral window where all the biogenic amino acids have a CD band of *one and the same sign*. As noted by Mason (1997) and Bailey et al. (1998), an enantioselective effect on amino acids is best obtained if the CPL spectrum is confined to a single CD band, because CD bands alternate in sign and sum to zero over the whole spectrum (the Kuhn-Condon rule: Kuhn, 1930; Condon, 1937). In the case of broad-band CPL, a net enantioselective effect may nevertheless result if the wavelength integral of the CD index weighted by the CPL spectrum yields a non-zero effective CD coefficient $\Delta\epsilon$ (Buchardt, 1974). To be at the origin of the biomolecular homochirality, the (effective) CD coefficient must be of the *same sign for all the biogenic amino acids*.

CD data for amino acids may be found in Legrand and Viennet (1965, 1966), Myer and MacDonald (1967), Katzin and Gulyas (1968), Anand and Hargreaves (1968), Horwitz et al. (1969), Sakota et al. (1970), Fowden et al. (1971), as well as in the references quoted by Blout (1973). Their general properties, along with the chromophore assignments, are summarized in Donovan (1969), Crabbé (1971) and Blout (1973). As already mentioned, the CD data of biogenic amino acids only should be examined in principle. However, as the composition of the set of biogenic amino acids is not currently known, we will discuss CD data of all natural amino acids, assuming biogenic amino acids are among them.

The optical activity of amino acids arises from the acid group chromophore bound to their α-carbon (i.e., a carboxyl group COOH in acid medium, that deprotonates in a neutral or basic medium to give a carboxylate group COO^-) and from possible supplementary chromophores located in their side chain. The CD spectrum of aliphatic amino acids (with side chains involving only C and H atoms without double bonds, i.e., alanine, valine, leucine and isoleucine) is quite simple, as it is due to the sole acid group chromophore bound to the α-carbon (Crabbé, 1971). By contrast, other amino acids exhibit a more complex CD behaviour because they possess a supplementary chromophore in their side chain (aromatic ring for phenylalanine, tyrosine and tryptophan; sulfur-containing group for cysteine and methionine; basic group for lysine, arginine and histidine; acid group for aspartic and glutamic acids; side chain closing back onto the α-amino group for proline) (see Donovan, 1969; Blout, 1973).

Because the pH of the medium modifies the amino acid by protonating or deprotonating the basic and acid groups (bound to the α-carbon or located in the side chain), the optical properties of amino acids depend on the acidity of the medium and on the nature of the solvent (Donovan, 1969). A sensitivity upon temperature (Horwitz et al., 1969) and upon ionization state (Katzin and Gulyas, 1968) has also been reported. Assuming that the acid group of amino acids in space occur in the form of a carboxyl group COOH rather than of a carboxylate group COO^- (since there is no reason for it to deprotonate as in neutral or basic solutions), CD measurements in acid medium should be considered when the optical properties of amino acids are dominated by their carboxyl chromophore.

As indicated in the references quoted above, laboratory measurements show that the carboxyl group bound to the α-carbon has a strong CD band centered

at about 210 nm. The sign of this CD band is directly related to the stereochemistry of the α-carbon and is thus the same for all L-amino acids. If this band were the only one involved in the asymmetric photolysis, the photolysis of amino acids would indeed favour the same enantiomer for all amino acids, and extraterrestrial asymmetric photolysis could indeed be considered as a viable explanation for the amino acid homochirality on Earth.

However, for non-aliphatic amino acids, the side chains complicate the picture as they introduce supplementary chromophores. The situation appears especially critical with tryptophan, whose indole chromophore exhibits a strong CD band centered at about 195 nm, with opposite sign to the carboxyl 210 nm band (Legrand and Viennet, 1965; Myer and MacDonald, 1967; Blout, 1973). Proline also has a strong CD band of opposite sign around 193 nm in a neutral solution (this band however disappears in acid solution; Fowden et al, 1971).

At this point, it should be stressed that Greenberg et al. (1994) have obtained an enantiomeric excess starting from racemic tryptophan in a laboratory experiment simulating photolysis by CPL irradiating an interstellar dust grain. The experiment was conducted at a temperature of 10 K with monochromatic light at 252.4 nm from a high pressure mercury lamp. Although that experiment certainly demonstrates the potential of CPL to trigger asymmetric photolysis of amino acids at the surface of interstellar grains, it does not ensure that an irradiation with broad-band UV CPL, as is more likely to be the case in space as discussed by Bailey et al. (1998), would still result in an enantiomeric excess (given the presence of CD bands of opposite signs in tryptophan). Moreover, in order to ensure homochirality with the other amino acids, the asymmetric photolysis of tryptophan should be governed by the carboxyl chromophore (210 nm) rather than by the indole chromophore (195 nm). This condition might be satisfied for an irradiation by UV light from main sequence stars later than about A8, but it does not necessarily hold true for irradiation by UV light from earlier stars whose flux raises shortward of 200 nm (Bailey et al., 1998). The same problem may arise in case of an irradiation by pulsar synchrotron radiation with a constant λF_λ spectrum (Rubenstein et al., 1983; Bonner and Rubenstein, 1987; Greenberg et al., 1994).

4. Conclusion: Asymmetric Photolysis vs. Composition of the Set of Biogenic Amino Acids

The present paper has reviewed the conditions necessary for the asymmetric photolysis of biogenic amino acids by CPL in space to be at the origin of today's homochirality of natural amino acids. It has shown that a critical requirement in that respect is that asymmetric photolysis should select the L-enantiomer for *all* the biogenic amino acids.

A survey of the available CD data for amino acids has revealed that tryptophan and proline pose the most serious problem, as they exhibit CD bands of opposite signs in the UV region where early-type main sequence stars emit most

of their radiation. Because the signs and intensities of CD bands depend however on the properties of the medium, extrapolation of laboratory data obtained in liquid solutions to infer the CD properties of amino acids in space (where they are likely to be found in solid or gas phase) is not straightforward, and prevents any firm conclusion to be drawn at this stage. Asymmetric photolysis laboratory experiments along the guideline of Greenberg et al. (1994), extended to other amino acids and using broad band UV CPL rather than monochromatic light, would be of great interest. As would be CD data for as many amino acids as possible, obtained under experimental conditions matching as closely as possible the conditions prevailing in space.

To summarize, the consideration of the available CD properties of amino acids currently leads to two mutually exclusive possibilities regarding the possible role of asymmetric photolysis in space for the homochirality of the natural amino acids: (i) if tryptophan or proline is biogenic, then the extraterrestrial asymmetric photolysis scenario has to be rejected, or (ii) if that scenario is valid, then the CD properties of amino acids (along with the spectral properties of CPL in space) allow to eliminate tryptophan and proline from the set of biogenic amino acids. This reasoning could be extended to any other amino acid for which new CD measurements in conditions mimicking those in space would uncover CD bands with a sign opposite to that of the carboxyl chromophore, in the spectral region characterizing CPL in space.

It is currently impossible to decide between the two alternatives, as there are experimental facts in support of each alternative. On the one hand, proline has been found in the Murchison meteorite (Kvenvolden et al., 1970; Engel and Nagy, 1982), which may be indicative of its biogenic nature if life started from the amino acids deposited on the early Earth, but on the other hand, some authors (Isoyama et al., 1984) have argued that tryptophan may have appeared quite late in the biological evolution.

In conclusion, we hope to have convinced the reader that the role of extraterrestrial asymmetric photolysis in the origin of the homochirality of natural amino acids on Earth, if at all involved, is far more complicated than is usually apprehended in the astronomical literature.

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